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GIS spatio-temporal modeling of human maritime activities

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Abstract

Coastal seas are important for human societies with many and diverse activities. These space and resource consuming activities exert an increasing pressure on the environment and sometimes result in conflicting interactions. Understanding these interactions remains a challenge for research and civil society. A methodology is proposed to describe the spatio-temporal distribution of several activities in coastal seas. An application is developed in the Bay of Brest (Brittany, France). Spatial, temporal, quantitative and qualitative data acquisition combines analysis of spatio-temporal databases and results from interviews. The heterogeneous data collected are stored in a spatio-temporal database (STDB). Firstly, the STDB is used with a GIS to produce temporal snapshots of daily human activity patterns over a one-year period. Secondly, using the STDB we can identify, quantify and map potential uses conflicts in space and time between activities in the Bay of Brest.

Introduction

Coastal seas play an essential role in human societies (Schwartz, 2005) where many and diverse activities take place (Katsanevakis *et al.*, 2011). These space and resource consuming activities interact with ecosystems and may modify their structure and functioning (Lotze *et al.*, 2006). These different activities may also result in conflicting interactions (Young *et al.*, 2007). Understanding these interactions is still a challenge for research (Leslie and McLeod, 2007) and civil society (UNEP, 2011). Pittman *et al.* (2012) identify priority needs such as relevant data collection, integration and analysis to describe the spatio-temporal distribution of activities in coastal seas in order to examine existing conflicts or anticipate potential conflicts. In recent years, spatial research on social dimensions of coastal and marine environments has progressed substantially (Koehn *et al.*, 2013). Integration of the temporal components in a multi-activities context is realized at macro and meso-scale (world to regional) in order to assess intensity indexes for each activity (Halpern *et al.*, 2008; Ban *et al.*, 2010; Stelzenmüller *et al.*, 2010; Kappel *et al.*, 2012). But at micro-scale, spatio-temporal approaches such as those conducted by Le Tixerant *et al.* (2010) in Iroise Sea (France), or by Longdill *et al.* (2008) in the Bay of Plenty (New Zealand), remain infrequent.

Our study aims to describe the spatial and temporal distribution of several maritime activities at a local scale in order to illustrate their dynamics. Our second objective is to assess the importance of their temporal dimension for identifying potential space-use conflicts. An innovative methodology is proposed to collect relevant data, to structure them in a spatio-temporal database and to model spatio-temporal interactions. An application is developed for the Bay of Brest (Brittany, France) chosen for its environmental and anthropic characteristics and for management purposes. First we identified the human activities taking place in the Bay of Brest and stored the available geographic data in a Geographic Information Base (GIB). Existing data describe aquaculture zones and mineral resources extraction areas. Spatial description of the other activities, however, cannot be provided, due to the lack of (accurate) data.

Methods

Data collection

Data collection aims to identify daily human activity patterns over a period of one year by their spatial, temporal, quantitative and qualitative characteristics. The year 2009 is chosen because of a higher availability of data. Data acquisition combines analysis of spatio-temporal databases such as automatic identification system (AIS) databases, and results from semi-structured interviews with stakeholders.

An AIS spatiotemporal database is used to identify marine transportation patterns (Le Guyader *et al.*, 2011). Combined with GIS spatial analysis, daily sea traffic for maritime transportation of goods and passengers in 2009 is identified, quantified and mapped.

For the description of organized activities such as commercial fishing, water sports (windsurfing, sailing, kayaking, rowing, scuba-diving) and maritime transportation of passengers, we decided to conduct an interview survey. For this purpose, we made use of a specific method to collect data provided by local stakeholders: semi-structured key informant interviews (Tremblay, 1957). Key informants were identified among representatives of organized activities and a non-random, stratified and purposive sampling is conducted. The total sampling effort is carried out on the basis of 30 interviews. The spatial distribution of activities is drawn directly on a tablet PC by stakeholders using GIS based mapping. During the interview, temporal, quantitative and qualitative data were also collected. Temporal data aim to establish presence or absence of an activity over the considered period (the year 2009) at a daily resolution. Quantitative data indicate the number of boats per day associated with this activity. Both types of data were collected in two ways: 1) "Real" data obtained from the databases of the organizations involved in our survey, 2) "Stakeholder-based" data provided by the key informants' description of an archetypal activity pattern (a typical year with a typical seasonality, and with typical weeks). Qualitative data concerning potential interaction between activities are collected and synthesized in a stakeholders-based interaction matrix.

Spatio-temporal database (STDB) structure

Given the heterogeneity of the collected data and the need to exploit them in a spatio-temporal perspective, data have been modeled into consistent information and structured into a spatio-temporal database (STDB) (Le Guyader, 2012). A Spatio-Temporal Unit (STU) is an elementary spatial unit associated with a thematic attribute. It is consistent with temporal and quantitative data. Spatial data containing the STUs are stored in a shapefile. Each entity corresponds to a STU and contains attributes relative to the geometry identifier, the activity identifier, the nature and the source of the geographic information. Daily occurrences of activities associated to quantitative data are stored in a table where each line contains an activity identifier, the date, the boat density, information on data quality, and a geometry identifier. These files are imported into a geodatabase and the geometry identifier is the key to the relation class. Then the STDB is used to describe daily human activities in the Bay of Brest in 2009. The description of these activities requires: (1) identifying and mapping the zones where activities take place, for each and every day during the year; (2) calculating and mapping the boat density distribution.

Each step of this process requires the application of spatio-temporal queries and the use of various geo-processing tools. To automate these tasks, two tools have been developed with ModelBuilder in ArcGIS.

Spatio-temporal conflict analysis

The identification of potential interactions between different activities at sea is realized by superimposing the activity zones (Brody *et al.*, 2004; Beck *et al.*, 2009; Stelzenmüller *et al.*, 2013). Spatial intersections are then related to different variables such as the cumulative number of activities, activity density per unit of surface area, presence/absence of potential conflicts or degree of potential conflict. The temporal dynamics of activities are not considered in these approaches. Our objective is to identify, quantify, qualify in time and space the potential negative interactions between maritime activities. The hypotheses are twofold: 1) activities potentially interacting are in a *spatio-temporal interaction* (they are taking place at the same place at the same time); 2) spatio-temporal interaction can be approached by computing spatio-temporal intersections. Such intersections have been calculated for the year 2009 at a daily resolution. A specific tool has been developed. It uses an algorithm written in Python and performs the calculation of the spatial intersections between STUs for each and every day during the year. Each entity of the resulting file contains information about the number of spatio-temporal intersections, the activities in question, the sum of boat density and the date. As activities in spatio-temporal intersections are not systematically in conflict, weights have been applied to spatio-temporal intersections (according to the key informants-based interaction matrix). The index value is binary: 0= no interaction, 1= potential negative interaction. Finally, to ensure the analysis of the spatio-temporal intersections, a spatial aggregation is performed on a uniform hexagonal lattice and identification of spatial outliers is carried out using local spatial autocorrelation measures (Anselin *et al.*, 2006).

Results

Collected data

GIS spatio-temporal analysis of the AIS database resulted in mapping 7 shipping lanes in the Bay of Brest for maritime transportation of goods and passengers in 2009. 32 interviews have been conducted to collect spatial, temporal, quantitative and qualitative data to describe the other organized activities, and 27 interviews aimed to map activity zones. 123 entities corresponding to the location of a given activity were drawn by 25 key informants. All activities were described under general conditions, except for water sports, also described under environmental constraints. Activity zones described by key informants have completed the GIB and they have been mapped. Afterwards, the 79 maps were sent to key informants for validation. Post-treatment of these heterogeneous data allowed us to map activity zones and to create an activities calendar associated with quantitative data for 29 activities.

Human activities in a spatio-temporal perspective

The STDB contains 149 STUs associated with 9,346 daily occurrences and describe 29 activities. Potential boat density associated with each occurrence has been calculated. Quality indexes for both occurrences and boat density, ranging from "very good" to "very low", have been estimated for each day. For 2009, the quality indexes range from "good" to "very good" for 84% of the days in terms of occurrences and for 90% of the days for boat density. The use of the STDB within a GIS provides temporal snapshots at daily time step over 2009 associated with data related quality indexes. The successive use of snapshots allows us to construct a spatially explicit representation of the human activities in the Bay of Brest over the entire year. In addition, it enables us to produce original information such as the spatial distribution of the cumulative sum of daily boat density over a year for a single activity or for several activities.

Spatio-temporal conflict between activities

Spatio-temporal intersections between activities have been calculated on a daily time step over the year 2009 ($n=552\ 757$). Intersections between potential conflicting activities represent less than 21%. Negative spatio-temporal intersections between transportation of passengers and organized leisure activities amount to 88%, between gill-net fishing for sea bass and transportation of passengers to 8.5%, between transportation of charges and organized leisure activities to 3%, between marine cultures and organized leisure activities to 0.4%, and between military activities and dredging fishery to 0.1%. Only one spatio-temporal intersection is identified between organized scuba diving and sportive nautical events. The analysis of the temporal evolution of the spatio-temporal intersections enables us to identify the presence of monthly and seasonal variations and to identify extreme values in 2009 by considering all activities either in their totality, or in pairs. For example, the annual extreme value for the daily sum of spatio-temporal intersections between transportation of passengers and organized leisure activities is reached on June 20th. The spatial analysis of the spatio-temporal intersections has led to map most significant clusters of high and low values ($p < 0.01$) by considering the whole year 2009 or for a given day.

A further analysis was conducted in order to balance information acquired by a spatial approach against information acquired by spatio-temporal approach for identifying potential conflict between maritime activities. Thus the most significant clusters of low and high values of the spatial intersections of activity areas were compared to those identified for the spatio-temporal intersections between activities in 2009. It was found that 70% of the most significant clusters identified by the spatial analysis of the spatio-temporal intersections are different from those identified by the spatial analysis of the spatial intersections of activity areas. These results show that integration of spatio-temporal dynamics of activities in identifying potential conflict between maritime activities provides a significant difference in the pattern when compared to a single spatial consideration.

Conclusion

Understanding interactions between activities and between activities and the environment involves a prior knowledge of the spatial and temporal patterns of activities at a fine scale. This study provides a methodology based on the collection and the integration of relevant data in a STDB. Applied in the Bay of Brest, its utilization with a GIS enables us to describe the spatio-temporal distribution of organized activities in a retrospective model on a daily time step over a period of one year (2009). In order to detect potential conflicts between activities, daily spatial intersections were calculated. The analysis of these spatio-temporal intersections allowed us to quantify the occur-

rences of intersections between activities, to put in evidence their temporal evolution and to detect where significant spatial clusters of low or high intersections are located. Even though taking into account human activity dynamics is time-consuming and quite complex, it provides more novel and more precise information than considering only the spatial component. Yet the assumption that potentially interacting activities are in a spatio-temporal interaction on a daily time step is certainly rough. That is why this method should be conducted at a finer time step and should take into account spatial uncertainty.

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